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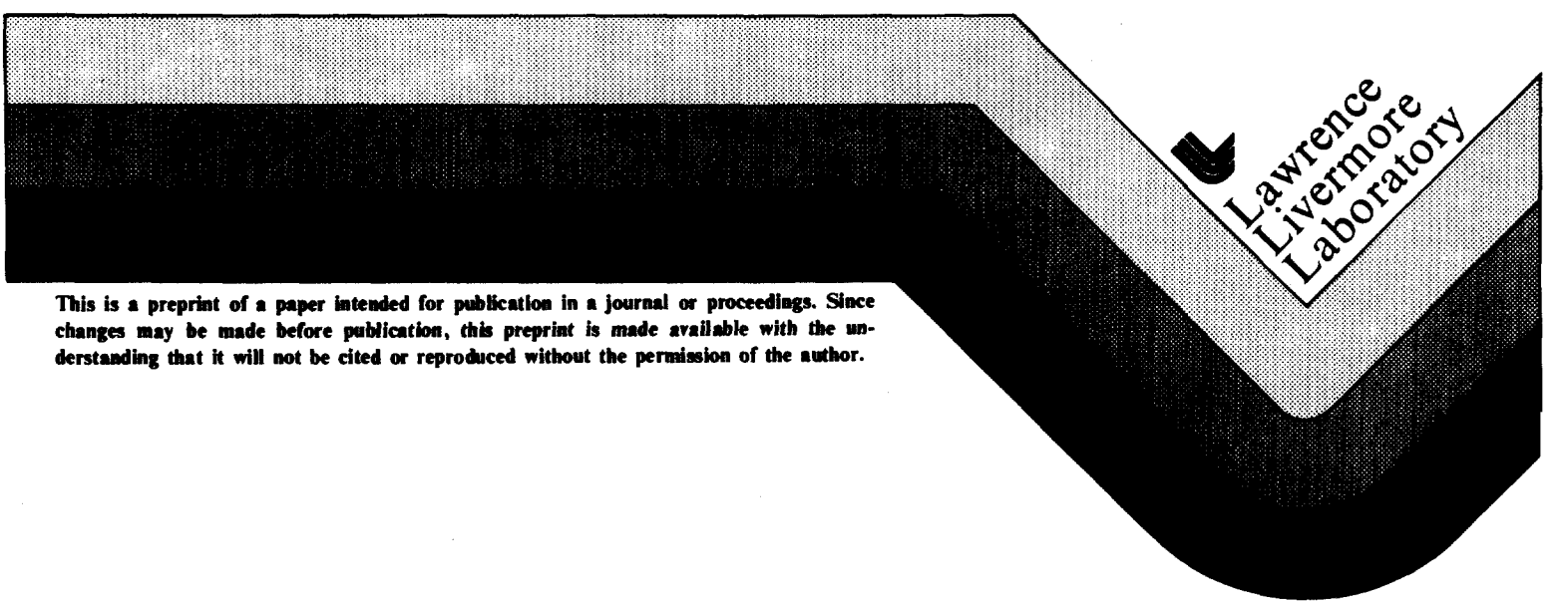

ALTERNATIVES FOR CONTAMINANT CONTROL DURING MFTF PLASMA BUILDUP*

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Introduction

This paper addresses contaminant control in the confinement region of the Mirror Fusion Test Facility (MFTF) currently being assembled at Lawrence Livermore Laboratory (LLL). The MFTF mirror device considers all low-energy species to be contaminants, since their primary effect is to erode the plasma boundary by charge-exchange reactions. Confinement for other than hydrogen isotypes is far from complete and confinement time is hardly more than transit time from the source to the end wall. The brevity of the confinement time makes it all the more necessary to prevent any contamination which might further reduce it. (In comparison, Tokamak fusion devices have long confinement times for high Z species, and are therefore concerned with radiative power loss.) At Livermore, the historical solution to contaminant control has been to evaporate titanium onto cold surfaces. We will consider an alternative to this approach and its implications.

Transport of Contaminants from the Wall to the Plasma

Several processes desorb atoms and molecules from the surfaces of the MFTF mirror device, making them available to contaminate the plasma. The yield of these processes is quoted in units of atoms or molecules per incident particle or photon. The total flux will naturally reflect the flux of incident particles or photons. The thermal desorption of molecules depends upon the surface temperature, and is related to the energy flux toward the surface and to such material characteristics as thermal conductivity.

For incident ions or neutral atoms two processes can be identified: ion-induced desorption (IID) and sputtering(S). Fig. 1 presents the yields for a variety of processes. The processes having the highest yield is ion-induced desorption. For surface coverages of many monolayers of contaminant (which have a low binding energy) the yield can be nearly 10^3. For contaminants that have a higher binding energy, the yield drops to approximately 1. Sputtering lies below 10^{-1}. The range of the curves follows the different surface binding energies of materials.

For incident electrons the process is referred to as electron-induced desorption (EID).[38-42] These values (see Fig. 1) appear to be lower than IID, but may approach them under low binding energy conditions for contaminants.

Photon-induced desorption (PID)[40-45] is probably a two-step process: first, a photoelectron is produced, then desorption is induced by the electrons. Consequently, PID has a yield lower than the EID yield.

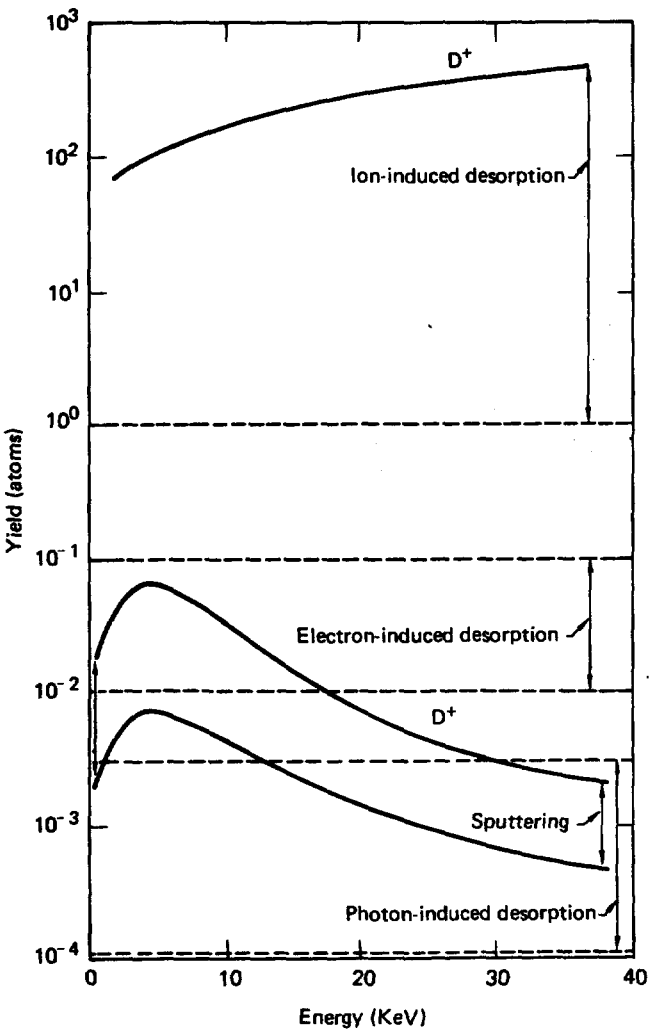

Fig. 1. Yield of transport processes.

Finally, thermal desorption may reflect any of the fluxes mentioned above, including infrared radiation. Thermal desorption at low and intermediate temperatures is a well-understood process, but at high temperatures (T > 500° C) volume diffusion of species to or away from the surface makes the process more obscure.[32,48,49,50]

An important variable governing which process is active and what its yield will be is the binding energy of the surface atoms. For energetic neutrals atoms, the yield can vary almost six orders of magnitude, depending on the value of binding energy in the range from less than 0.5 eV to 8 eV.

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It is therefore apparent that any surface intended to minimize contamination to the plasma should have as high a binding energy as possible. If this condition is met, the yield from all processes will be reduced to its lowest level.

Among the choices of materials available, considering other requirements of bulk deuterium storage, are several hydride-forming metals. Two methods may be used to obtain a clean metallic surface: creating it by an evaporation-condensation process or cleaning a bulk surface. In the next subsections we will present specific cases employing these two methods: titanium evaporation and a heated-liner concept employing zirconium.

Titanium Gettering Case

Evaporation of fresh layers of titanium onto surfaces exposed to the plasma prior to a plasma pulse satisfies the requirement for a clean surface with high binding energy. The titanium reacts with water vapor and oxygen already on the surface to produce oxides of titanium. A pure titanium surface can be achieved by further evaporation. Under these conditions sputtering would be the only active process.

Heated-Liner Case

An alternative to evaporating titanium is to produce a clean surface on a bulk metal facing the plasma. The use of bulk material allows the storage of deuterium, if a hydride-forming metal is employed. Surface saturation is prevented if hydrogen diffusivity is high, as it would be for some materials at slightly elevated temperatures.

Considering the foregoing constraints and requirements, we propose that zirconium sheet be employed. At temperatures near 700° C surface oxygen will diffuse in to the bulk, leaving only a thin surface layer of carbon and no hydrogen. These thin layers could be removed by glow-discharge heating in hydrogen if they prove troublesome. This would only be necessary after exposure to air or gases released from the cryopanels. Under normal condtion, a modest temperature could be maintained, which would allow diffusion of the deuterium into the bulk of the zirconium sheet.

To make a more concrete comparison between the titanium gettering and the heated zirconium liner, we discuss the practical aspects of both in the following sections.

Engineering Problems With Titanium Gettering

Many of the engineering problems associated with titanium gettering are inherent in the technique; when it is applied to MFTF, some additional specific problems arise.

First, consider the wire used as a titanium source. The present state-of-the-art wire is Ti-15 Ta alloy. While its mechanical characteristics, particularly post-gettering ductility, are definitely superior to those of other alloys, the evaporation rates and lifetime obtained are quite sensitive functions of its mechanical and electrical properties. Composition variations, both initially and after a period of use, further complicate understanding. It is essential to test each lot of wire to ascertain how it may behave and to produce reasonable (by no means precise) estimates of its gettering rate and expected lifetime. Small variations in the physical properties of the wire have a disproportionately large influence. (Since the evaporation rate varies by 1.7% for each 1 K change in temperature at its operating temperature of about 1800 K, this is not surprising.) Table 1 lists some of the major physical-property influences on gettering rate, and more detailed description is given in references 51 and 52.

We conclude from Table 1 that it is essential to maintain a record of time on and current levels for each wire in use, to predict replacement intervals. Recording such a history can be a substantial instrumentation investment and data-handling problem.

Table 1. Evaporation rate sensitivity

Parameter	Nominal Value	Uncertainty	Power Supply Modes ΔE/E, % for +1% changes in Parameters: Constant Power	Constant Voltage	Constant Current
Power*	2500 W/m		+7.6%	--	--
Voltage*	24 V/m		--	+13.4%	--
Current*106 A (new wire)		--	--	+18.7%	
Diameter	0.318 cm	2%	-7.6%	+ 6.7%	-28.0%
Length**	--	1%	-7.6%	-13.4%	--
Emissivity	0.42	20%?	-7.6%	- 6.7%	- 9.4%
Resistivity ($\rho = \alpha + \beta T$)	α 3.5×10^{-7} Ω -m	20%?	--	- 1.5%	+ 1.9%
	β 7.7×10^{-10} Ω -m/K	20%?	0	- 4.8%	+ 7.5%

*The drive in either of the 3 power supply operating modes is adjusted according to an empirically established schedule to maintain a "uniform" evaporation rate. Values listed show the evaporation rate change with control capability of 1%.

**During the early part of its life, the wire length may grow by 1%. Shrinkage of as much as 12% has been observed late in the wire life.

The surfaces to be covered with Ti need to be properly treated to promote adhesion. Since at least a few monolayers must be deposited before each plasma pulse, and since deposition of the Ti is not uniform (about a factor of 3 variation in thickness), buildup of Ti to the order of 25μm (1 mil) can occur in less than a year's time. At this thickness the Ti may start to peel off, requiring cleaning of the surfaces onto which the deposition was performed. In MFTF these are the water-cooled surfaces of the magnet liner. Their removal is formidable, making maintenance requirements for Ti gettering substantially more complicated than the (relatively) simple replacement of the wire itself.

A last general problem with Ti gettering is that the Ti will go where it is not wanted. In MFTF both neutral-beam sources and diagnostics will be afflicted by Ti pollution and protection must be provided.

Figure 2 is a plan view of MFTF, showing the getter-assembly locations relative to the magnet. Eight assemblies are used; they are oriented at roughly 45° to gravity. They must be moved into the plasma region (a distance over 6 m), operated, and retracted immediately prior to each plasma pulse. They are to have a ten-year operational life (about 100,000 cycles).

These requirements present a challenging mechanical engineering and design problem. The mechanism includes a vacuum-seal, bearings, drive assembly and current leads; life testing of a prototype assembly is planned.

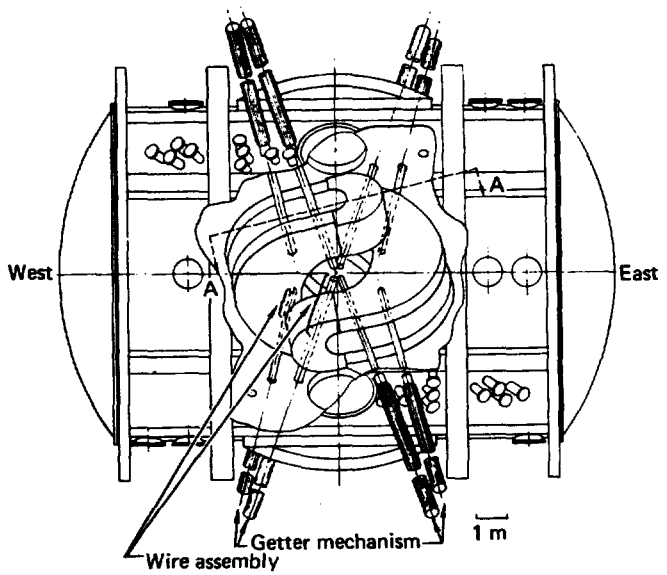

Fig. 2. Plan view of MFTF. A-A is the cut plane for Fig. 3.

Because the evaporation is performed in magnetic fields of about 5.8 T (central field 2 T), high frequency (10 kHz) power must be used. The high fields and gradients also produce very large magnetic forces on assembly components, further restricting the design latitude.

Implementation of the Heated Zirconium Liner Concept

The regions surrounding the plasma to which heated liners would be applied are shown in Fig. 3. Although in fact the heat flux distrtibution forms a continuum, for simplicity it is treated here as a high-heat-flux region ($\approx$100 W/cm^2, mostly by charge-exchange neutrals) and a low-heat-flux region ($\approx$10-20 W/cm^2). The high-heat-flux region is about 6 m^2 of grazing incidence and 4 m^2 of normal incidence; the low heat flux region is about 30 m^2 of grazing incidence and 10 m^2 of normal incidence. It may not be necessary to install the heated liners over all of the low-flux region.

The entire magnet is surrounded by liquid-nitrogen-cooled liners; all of the regions shown are further guarded by water-cooled liners. The heated liners would be physically mounted on these water liners. The two magnet-liner systems together weigh about 130 KN (30,000 pounds); the water liners are designed for steady-state heat loads of 100 W/cm^2. The heated-liner system would increase the liner mass by less than 5%.

The present estimates of the gross-average view factor of the heated liners for objects external to the magnet is about 0.5. A three-dimensional Monte Carlo analysis of view factor and power balance as a function of position on the magnet surfaces is in progress. Heat used to maintain the liners at elevated temperatures would be taken out primarily at room temperature; because differential pumping baffles have been installed outside to the magnet, very little additional loading of the cryopump's liquid nitrogen circuits is expected.

The proposed heated liner consists of modules, each about 0.6 m × 0.6 m, of 0.16 cm (1/16") Zr sheet. Each sheet would have linear heating elements on one side. These could be parallel Zr tubes brazed to the surface, containing ceramic-insulated wires. The spacing of the Zr tube heaters would be based on a cost/temperature uniformity trade-off. The sheets would be mounted to the water liners with adequate thermal isolation to prevent local hot spots on the water liners.

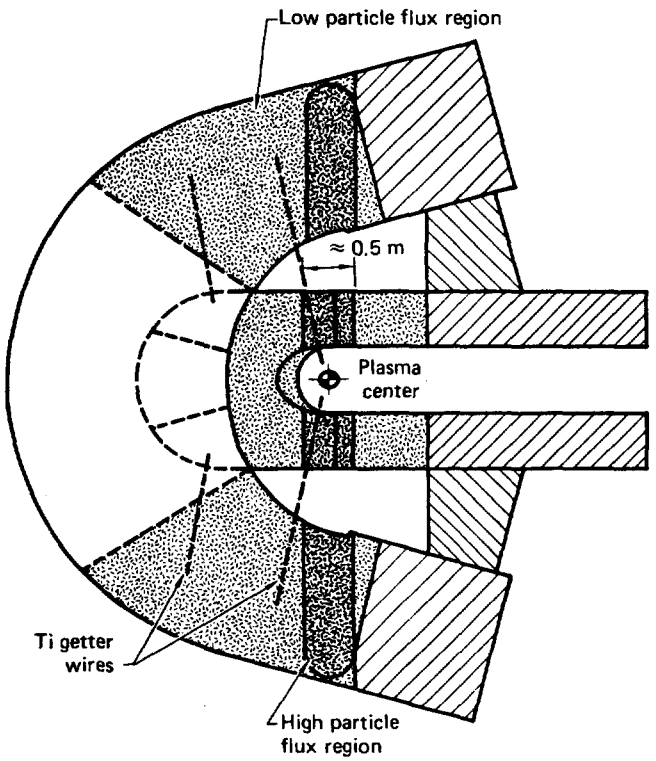

Fig. 3. MFTF magnet structure (Section A-A of Fig. 2).

The initial operational step of heating the liners to approximately 700 K to diffuse surface oxides into the bulk requires about 100 kW. This process is repeated after each cryopanel regeneration (2-3 week intervals). When the magnetic field is off, this can be 60 Hz power; if the process must be repeated between regenerations, dc power appears acceptable. The heater wire circuit can be configured to minimize magnetic forces. Note that this procedure is only required for those portions of the liner subjected to low particle fluxes. The consequent heat load on the water liners is about 0.25 W/cm^2.

Steady-state power is required to raise the temperature of the liners in the low flux region to≈ 100 °C (400 K). Less than 10 kW of dc power is required. Even if it were all absorbed at LN_2 temperature, the effect on LN_2 consumption (30 kW for cryopanels, 100 kW for the entire system) is negligible.

No steady-state or oxide-diffusing power appears to be necessary to the liners in the high heat-flux region (although the capability would be included for initial machine shakedown and startup). Figure 4 gives the temperature history of the liners in this region after equilibrium-ratcheting has occurred. In some areas, startup beam impingement causes an additional heat load of 3 kW/cm^2 for 10 ms at the start of the plasma pulse, and the effect of this on the surface temperature is shown in dashed lines.

Current Status of MFTF Plans

The alternative of a heated zirconium liner for the confinement region of MFTF seems attractive, although a number of questions concerning quantitative aspects and thermal interactions between the liner and the system remain to be answered. Work is now being planned to obtain these answers. In the interim, the primary containment control method will continue to be titanium evaporation, which has served this purpose in mirror devices for many years.

Application of the Heated Liner to Tritium Experiments.

The heated-liner alternative provides an interesting option for tritium experiments which minimize the hazards associated with inventory and personnel exposure. This alternative allows the tritium to be selectively stored (low liner temperature) or released (high liner temperature) so that there is little tritium refluxing to complicate the experiments, and so that the tritium can be removed from the system before maintenance or modification.

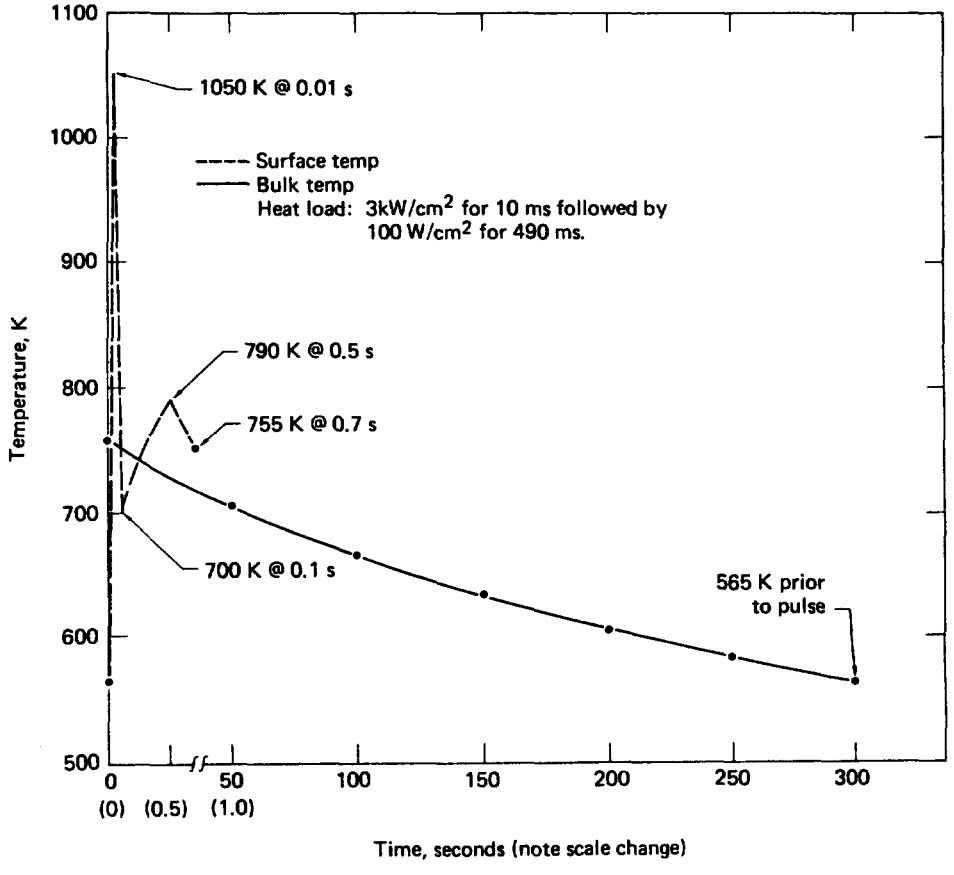

Fig. 4. Magnet liner temperature history after equilibrium-ratcheting has occurred in the high particle flux region.

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